OPERATING AND MAINTENANCE
INSTRUCTIONS

for

TYPE 1611-A CAPACITANCE TEST BRIDGE

GENERAL RADIO COMPANY
275 MASSACHUSETTS AVENUE
CAMBRIDGE 39 MASSACHUSETTS
U.S.A.

OPERATING AND MAINTENANCE INSTRUCTIONS

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TYPE 1611-A CAPACITANCE TEST BRIDGE

Form 668-E
April, 1955

GENERAL RADIO COMPANY
275 MASSACHUSETTS AVENUE
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Printed in U.S.A.

Digitized by the Internet Archive
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https://archive.org/details/manualsplus_06666

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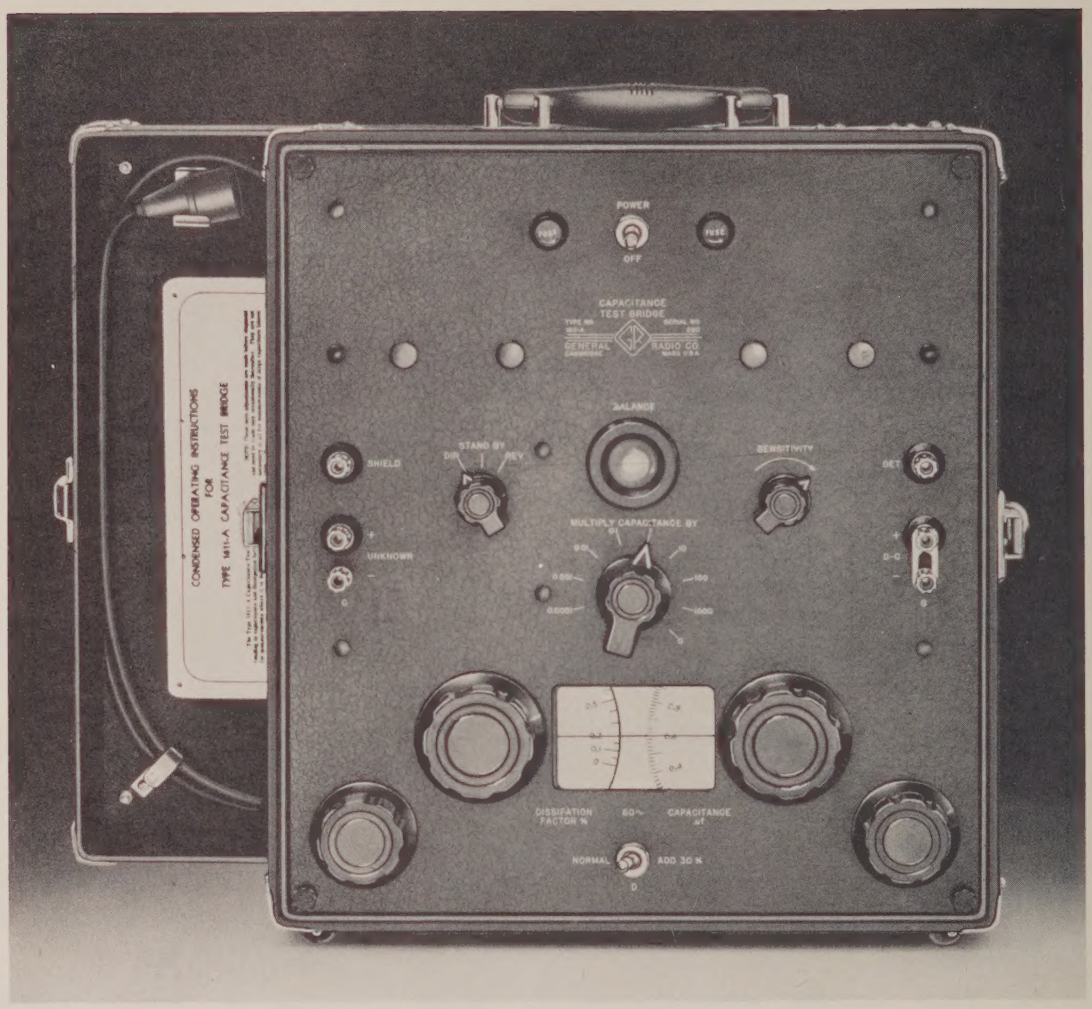


SPECIFICATIONS

Capacitance Range: 0 to 11,000 μf, covered by eight multiplier steps and an approximately logarithmic, direct-reading dial.

Dissipation-Factor Range: 0 to 60% (at 60 cycles), covered by one dial having an approximately logarithmic scale, and a switch.

Capacitance Accuracy: $\pm(1\% + 1\ \mu\mu f)$ over the entire range of the bridge.

Dissipation Factor Accuracy: $\pm$(2% of dial reading + 0.05% dissipation factor). Power Factor $= \dfrac{D}{\sqrt{1+D^2}}$, where D = dissipation factor.

Sensitivity: The sensitivity is such that any capacitance in the range 100 $\mu\mu$f to 10,000 μf can be balanced to a *precision* of at least 0.1%.

Temperature and Humidity Effects: The readings of the bridge are unaffected by temperature and humidity variations over the range of room conditions normally encountered (65° F to 95° F, 0 to 90% RH).

A-C Voltage Applied to Capacitance under Test: The voltage impressed on the unknown capacitance varies from a maximum of approximately 125 volts at 100 $\mu\mu$f to less than 3 volts at 10,000 μf. The circuit is so arranged that a maximum of one volt-ampere of reactive power is delivered to the sample.

Polarizing Voltage: Terminals are provided for connecting an external d-c polarizing voltage. The maximum voltage that should be impressed is 500 volts.

One of the terminals is grounded so that any a-c operated power supply with grounded output can be used. The terminal capacitances of the power supply do not affect the bridge circuit.

Power Supply Voltage: 105 to 125 (or 210 to 250) volts, 60 cycles.

Power Input: 15 watts.

Accessories Supplied: Line connector cord.

Mounting: Portable carrying case of luggage-type construction. Case is completely shielded to insure freedom from electrostatic pickup.

Vacuum Tubes: One each 6X5-GT, 6SJ7, and 6U5. All are supplied.

Net Weight: 30½ pounds.

Dimensions: (Width) 14½ x (depth) 16 x (height) 10 inches, overall, including cover and handles.

OPERATING and MAINTENANCE INSTRUCTIONS

for

TYPE 1611-A

CAPACITANCE TEST BRIDGE

SECTION 1.0

DESCRIPTION OF ELECTRICAL CIRCUITS

1.1 GENERAL

The Type 1611-A Capacitance Test Bridge is a direct-reading capacitance bridge covering an unusually wide range from one micromicrofarad to 11,000 microfarads. It contains a visual detector, and the measurement is made at the power-line frequency, so that no accessories are required. It is merely necessary to connect the instrument to the power line, to connect the unknown capacitance to the bridge, and to adjust the direct-reading controls until balance is indicated by minimum deflection of the electron-ray tube ("magic eye").

1.2 THE BRIDGE CIRCUITS

The circuit employed is the series-resistance type of capacitance bridge, wherein the unknown capacitance is measured by variable resistance arms in conjunction with a fixed standard capacitor, and the dissipation factor is measured by a variable resistor in series with the standard capacitor. In order to cover effectively the extremely wide capacitance range, two bridge circuits are used, differing in the value of the standard capacitance used and in the method of connecting generator and detector. The necessary changes in circuit connection are all made by the bridge panel controls.

1.21 Low Capacitance Multipliers: Figure 1a shows the basic bridge circuit arrangement used for the four lower multiplier positions (.0001, .001, .01, .1).

1.22 High Capacitance Multipliers: Figure 1b shows the arrangement used for the four high multipliers. The generator and detector have been interchanged from the circuit of Figure 1a and the capacitance and resistance of the standard arm have been changed by a factor of 100.

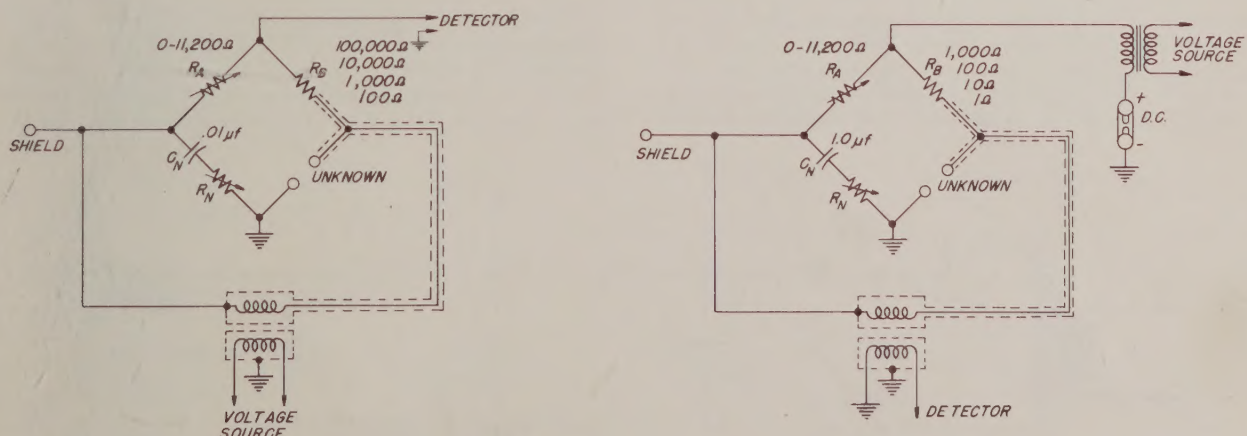


Figure 1. Basic Bridge Schematics for (a, left) the Four Lower Multiplier Positions, and (b, right) the Four Higher Multipliers.

With this connection, there is provision for connecting in series with the a-c bridge voltage a d-c voltage for polarizing electrolytic capacitors. The circuit is so arranged that one terminal of the d-c source is at ground potential, thus permitting the use of practically any available d-c source, either batteries or a-c operated power supply. This arrangement avoids the necessity for a high-impedance choke, which is required by methods commonly used.

1.3 THE DETECTOR

The detector system consists of a single stage of amplification and an electron-ray tube ("magic eye") which is used as a visual indicator. As shown in Figure 2, the amplifier is made selective to the operating frequency by means of a parallel resonant circuit in the plate circuit. The detector system is designed to be very sensitive when the bridge is at or near balance, but relatively insensitive when the bridge is out of balance. This is accomplished by the use of a "remote cut-off" type of electron-ray tube (Type 6U5) in conjunction with a voltage-sensitive resistance element (Thyrite) shunting its input. The resulting characteristics greatly simplify the process of locating the balance, and the necessity of using the manual sensitivity control is greatly reduced.

1.31 The detector can be disconnected from the bridge by turning the multiplier switch to the DET position. It can then be used as a null detector for any other 60-cycle bridge. Its input is between DET binding post and G.

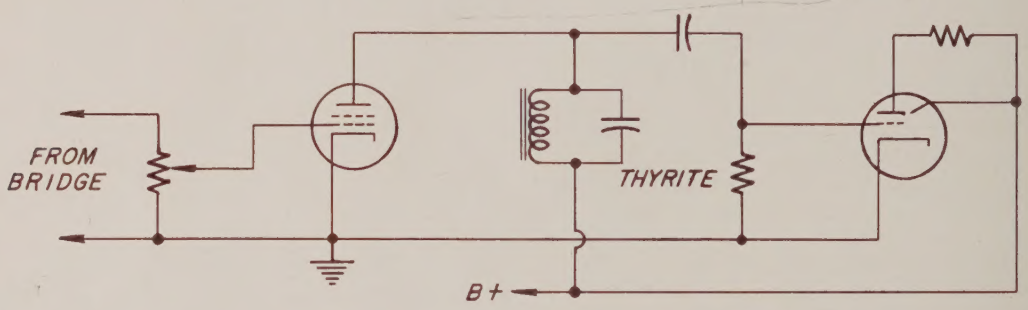


Figure 2. Detector System Schematic Showing Resonant Circuit Used for Frequency Selectivity

1.4 D-C POWER SUPPLY

The d-c voltages required by the amplifier are provided by the entirely conventional circuit of Figure 3. It consists of a transformer, a half-wave rectifier, and a resistance-capacitance filter.

1.5 BRIDGE VOLTAGE SUPPLY

Because of the very wide range of impedance presented by the bridge, no single source of voltage can be capable of efficiently supplying the test voltage for all ranges. Four separate sources are provided, one for each pair of the eight multiplier positions. The voltages and series resistances are chosen to deliver approximately the maximum safe power to the bridge under all conditions. Figure 4 shows schematically how these are obtained. The proper source is selected by a switch mechanically connected to the switch that controls the ratio arm of the bridge. The approximate voltages applied to the unknown capacitor are given in Table I.

1.6 COMPENSATING CIRCUITS

1.61 Ratio-Arm Compensation: Any loss in the standard capacitor causes the bridge to read low in dissipation factor by an amount equal to the dissipation factor of the standard capacitor. Since this value may be as much as .0012, it must be compensated in order to

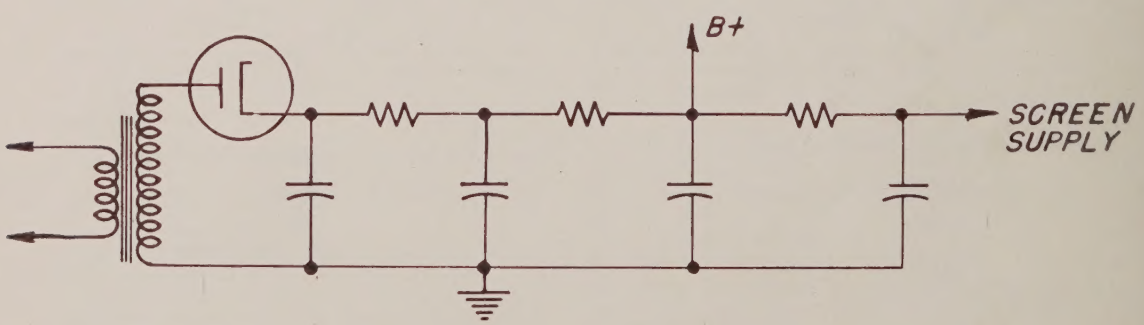


Figure 3. Power Supply Schematic Diagram.

TABLE I

Multiplier	R_B	I_M	C_N	Volts applied to unknown, with C dial at	
	Resistance	Max. Current		Min.	Max.
.0001	100,000 ohms	1.5 ma	.01 μf	128	121
.001	10,000 ohms	5 ma	.01 μf	57	43
.01	1,000* ohms	16 ma	.01 μf	13	5
.1	100 ohms	55 ma	.01 μf	1.5	.5
1	1,000 ohms	16 ma	1.0 μf	22	5
10	100 ohms	55 ma	1.0 μf	12	1.5
100	10 ohms	170 ma	1.0 μf	2.4	.5
1000	1 ohms	550 ma	1.0 μf	1.4	.15

R_A resistance in kΩ equals dial reading in μf.

realize the rated accuracy of the bridge. Compensation is accomplished by connecting fixed capacitors across the resistors in the opposite arm*, of such value that the product $R_B\omega C_B$ approximates D_0, the dissipation factor of the standard capacitor.

1.62 Zero-Capacitance Compensation: A unique compensating circuit is used effectively to eliminate the zero capacitance and losses across the UNKNOWN terminals. This circuit makes possible direct reading of capacitance and dissipation factor, on the lowest multiplier, with no necessity for "zero" corrections.

As shown in Figure 5, a voltage of adjustable magnitude and phase is fed to the bridge output. This voltage is adjusted to cancel the unbalance voltage produced by the zero capacitance and resistance. It also serves to compensate partially for any leakage through the bridge transformer, as well as any small voltage "picked up" by the amplifier through capacitive coupling to high voltage leads.

* No compensation is used on the 1-ohm and 10-ohm resistors corresponding to the 100 and 1000 multipliers, since the dissipation factor of the standard capacitor associated with those multipliers is only .0003.

1.7 EQUATIONS OF BALANCE

The balance conditions are independent of generator and detector connections. They are given by

$$C_{xs} = C_N \frac{R_A}{R_B} \qquad (1.1)$$

$$D_x = R_x\omega C_x = R_N\omega C_N = D_N \qquad (1.2)$$

where C_{xs} and D_x are the series capacitance and dissipation factor of the unknown capacitor, and C_N and D_N are the series capacitance and dissipation factor of the standard arm.

1.8 COMPLETE CIRCUIT DIAGRAM

The complete wiring diagram of the instrument is given in Figure 11.

1.9 BRIDGE ARM CONSTANTS

The constants of the various elements for each multiplier position are given in Table I.

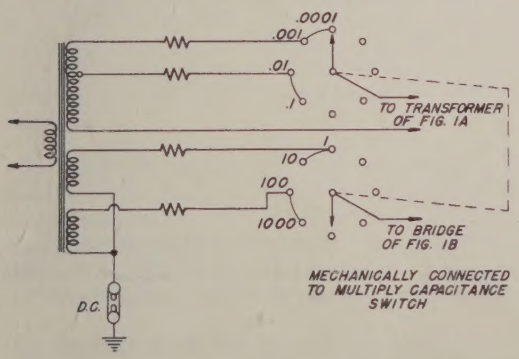


Figure 4. Schematic Showing Bridge Voltage Sources and How They are Switched by the Range Switch.

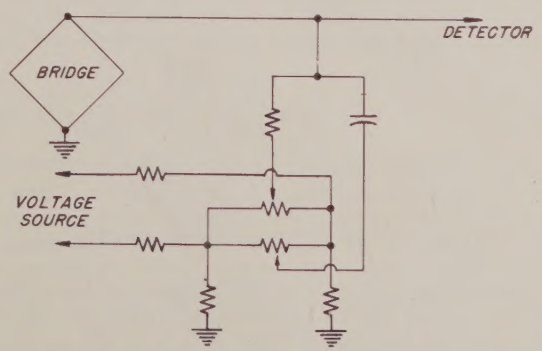


Figure 5. Schematic Diagram of Zero-Capacitance Compensation Circuit.

SECTION 2.0

MECHANICAL ARRANGEMENT

2.1 GENERAL

The instrument is housed in a shielded cabinet of the so-called "airplane-luggage" type. A cover is provided, which protects the panel and controls when the instrument is carried about and also prevents the accumulation of dust when it is not in use. Simplified operating instructions are mounted in the cover, as is the power cord.

The operating controls are conveniently grouped near the bottom of the panel. The two dials are so arranged behind the panel that a portion of each is visible through a centrally located window. The readings are thus taken at a glance; and since each dial is direct-reading, there is little likelihood of misinterpreting readings.

2.2 THE STANDARD CAPACITORS

As noted in Sections 1.21 and 1.22, two standard capacitors are used. One is a .01-μf mica capacitor, Type 505, mounted on the subpanel (see Figure 13). The other is a special 1.0-μf unit using polystyrene tape as the dielectric material, and made in two 0.5-μf sections. After special heat treatment, aging, adjustment, and impregnation, it is mounted and sealed in the cylindrical metal containers located under the main shelf, as shown in Figure 13.

2.3 THE DISSIPATION-FACTOR RHEOSTATS

The two rheostats (one for each capacitor) used to balance for dissipation factor are ganged to a common shaft and mounted on the subpanel (see Figure 13).

Each rheostat winding consists of two tapered sections. The resistances of the two sections are so chosen that the resulting scale permits precise readings at low values of dissipation factor, while at the same time retaining the convenience of having the range up to 30% on a single scale. An etched dial scale is used and four adjustable shunt resistors are provided, one across each section of each rheostat, to bring the actual resistance into agreement with the value required by the scale.

Two resistors controlled by a double pole switch are connected one to each rheostat in order to increase the dissipation factor range from 30% to 60%.

2.4 THE "A" ARM

The variable resistor R_A, by means of which the capacitance balance is obtained, is a tapered rheostat having a total resistance of approximately 11,000 ohms (see Figure 14). The taper is such that the scale of the dial is approximately logarithmic. An adjusting plate and cam are built into the unit which permits an adjustment of the position of the arm with respect to the dial, at eight points. As adjusted at the factory, the resistance in kilohms corresponds to the dial reading within $\pm$0.5% over the main decade from 1.0 to 10.

2.5 THE BRIDGE TRANSFORMER

A shielded transformer is used to couple the voltage source to the bridge (Figure 1a) or the bridge to the detector (Figure 1b). An electrostatic shield surrounds each winding, insuring a very low electrostatic coupling between windings. The primary shield is grounded, and the secondary shield is connected to the bridge. The secondary shield-to-ground capacitance is part of the standard capacitance arm. For this reason the transformer is wound with polystyrene tape as insulation to insure a low and constant dielectric loss.

The transformer is encased in a high-permeability case to minimize magnetic coupling to the rest of the circuit and to any external fields (see Figure 14). The entire assembly is treated and impregnated to minimize the possible effects of moisture.

2.6 THE "MAGIC-EYE" TUBE

The electron-ray tube (Type 6U5) is so mounted in a slotted tube that its position with respect to the panel can readily be changed. It is held in position by a thumbscrew which is accessible when the instrument is removed from its case. When the bridge is used in very brightly lighted locations, or when the brilliance of the eye has been reduced with age, the tube can be slid back in its mounting to provide additional light shielding.

SECTION 3.0

NORMAL DIRECT-READING OPERATION

3.1 SETUP AND PRELIMINARY ADJUSTMENT

3.11 Power Connection: Connect the bridge to a suitable power source as indicated on the plate under the power receptacle (either 115 v. or 230 v., 60 c) with the seven-foot line connector cord mounted in the cover, and turn the POWER switch on.

3.12 Grounding: Connect one of the G terminals to a good ground. Such ground connection is recommended for best results although not always necessary.

3.13 Zero Adjustment: Set the CAPACITANCE MULTIPLIER to .0001, the CAPACITANCE dial to zero, and the SENSITIVITY control to maximum. With the

control switch set at DIRect, adjust the two potentiometer controls under the snap buttons at the upper left of the panel for zero deflection of the eye. The left control is for dissipation factor, the right for capacitance. Set the control switch to REVerse and adjust similarly the two right-hand potentiometer controls. The bridge is now ready for measurements.

Note: These zero adjustments have been made at the factory and in general need to be checked only occasionally. When the best possible accuracy is desired, especially for the measurement of small capacitance, or if the bridge is used as in 3.131, it is well to check the zero adjustment more frequently.

Although capacitance less than 1000 $\mu\mu$f should normally be measured on the 0.0001 multiplier, it is sometimes more convenient to use the 0.001 range. In this case the zero adjustment should be made on this multiplier in the same manner as above.

3.131 Lead capacitance may be included in the zero adjustment when desired. Connect the unknown capacitor as indicated in 3.21, but with the high lead disconnected at the capacitor terminal, before making the above adjustments. A capacitance of about 15 $\mu\mu$f may be compensated in this manner.

When the lead capacitance is larger than 15 $\mu\mu$f, as from long leads or a cable, its effect on the measured values of capacitance and dissipation factor can be eliminated by measuring the lead or cable alone. Let these values be C_e and D_e. Then the unknown capacitance and its dissipation factor are given by the formulae:

$$C_{xs} = C - C_e \qquad (3.1)$$

$$D_x = \frac{DC - D_eC_e}{C - C_e} \qquad (3.2)$$

where C and D are the values with the unknown connected.

3.2 MEASUREMENT OF UNKNOWN CAPACITANCE

3.21 Connection: Set the control switch to STAND BY to remove voltage from terminals. Connect the capacitor to be measured to the UNKNOWN terminals. Make sure that the low, or ground, terminal of the unknown is connected to the Ground terminal of the bridge.

3.22 Balance Procedure: Set the control switch to DIRect. If the nominal value of the capacitor being measured is known, set the MULTIPLY CAPACITANCE BY switch to the appropriate point, then adjust the CAPACITANCE and DISSIPATION FACTOR controls to reduce to a minimum the deflection of the null indicator.

3.221 If the capacitor being measured is completely unknown, the surest procedure to locate the balance point is as follows: set the MULTIPLY CAPACITANCE BY to the highest point (1000) and adjust the CAPACITANCE dial for approximate null balance. If the balance occurs below 1.0 on the dial, turn to successively lower MULTIPLIER positions until the balance falls in the main decade (1.0 to 10) of the dial.

3.23 Sensitivity Control: Because of the limiting action of the null indicator circuit, relatively little manipulation of the SENSITIVITY control is required. A convenient initial setting is that at which the eye just closes without overlapping. After the approximate balance has been located, the SENSITIVITY control can immediately be advanced to the maximum necessary amplifier gain.

3.24 The Control Switch: The DIRect and REVerse positions of this switch provide opposite polarities of the voltage applied to the capacitor under test. It provides a means of eliminating the effect of extraneous voltages that may be induced (usually electrostatically) in the capacitor under test from adjacent electro-magnetic fields at the power-line frequency. If such induced voltages are present, different readings of the bridge will be obtained for the DIRect and REVerse positions. For moderate deviations (less than 10%), the true result is the average of the readings for the two polarities.

3.241 The complete formulae, applicable for strong interference which results in large differences in reading, are:

$$D_x = \frac{D_1C_1 + D_2C_2}{C_1 + C_2} \qquad (3.3)$$

$$C_{xs} = \frac{C_1 + C_2}{2} \qquad (3.4)$$

These formulae are based on parallel capacitance, as discussed in Section 4.41. The maximum voltage allowable is that which causes one of the controls, usually that for dissipation factor, to read negative. Hence the larger the true dissipation factor, the greater the interference which can be tolerated.

3.242 In the STAND BY position, the test voltage is removed from the UNKNOWN terminals on the four lower multipliers. On the four upper multipliers, the switch is inoperative, but the available voltage is low.

3.25 The accuracy of capacitance readings is $\pm$(1%+1$\mu\mu$f) over the entire range from 1$\mu\mu$f to 10,000μf.

3.3 MEASUREMENT OF DISSIPATION FACTOR AND SERIES RESISTANCE

3.31 Dissipation Factor: The DISSIPATION FACTOR dial is calibrated to read in per cent, both because that method is widely used in the electric power and communication industry and because such calibration eliminates the use of decimal points. In all unmodified formulae the reading in per cent must be expressed as a ratio by dividing by 100.

3.32 Series Resistance: Since the bridge measures series capacitance, the series resistance of the unknown capacitors is given by the formula:

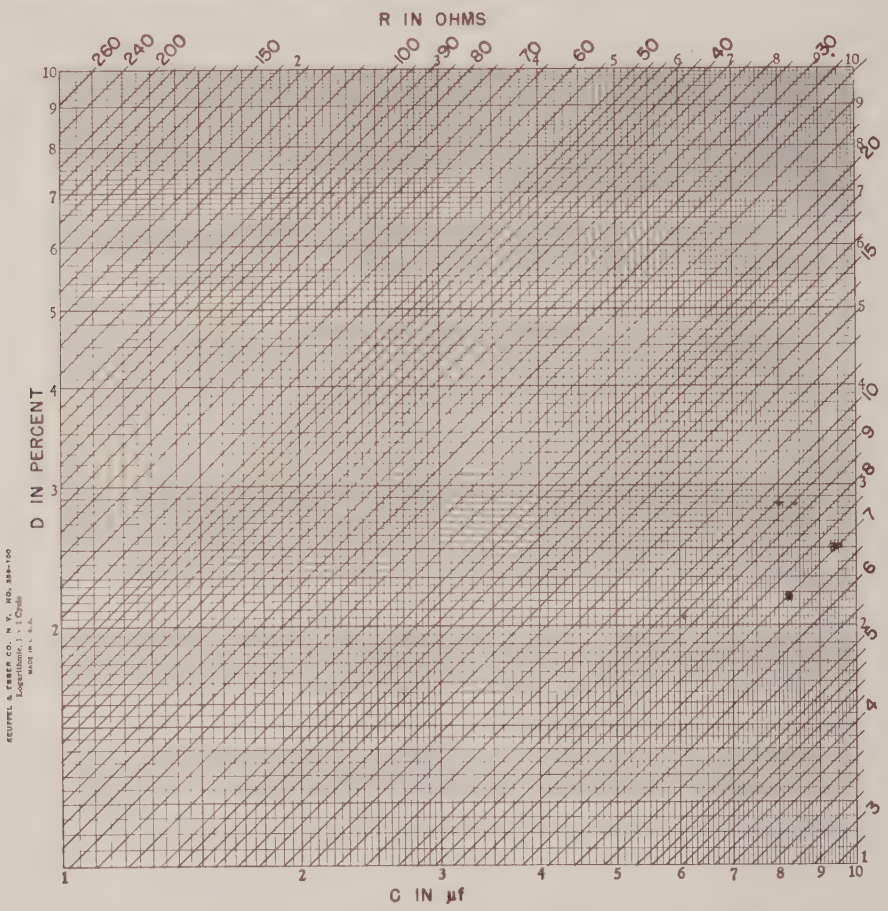
$$R_{xs} = \frac{D_x}{\omega C_{xs}} \quad \Omega \text{ (c, f)} \qquad (3.5)$$

at 60 cycles

$$R_{xs} = \frac{26.53 D_x}{C_{xs}} \quad \Omega \text{ (\%, } \mu\text{f)} \qquad (3.6)$$

The following charts, Figure 6, can be used to determine series resistance graphically for any pair of values of series capacitance and dissipation factor. The small chart at the bottom is used to determine the order of magnitude while the larger chart, which covers only a single decade of capacitance and dissipation factor, is used to obtain significant figures.

3.33 The accuracy of dissipation factor readings is ±(2% of dial reading + .05% dissipation factor) over the entire range from .05% to 60% for all capacitances greater than 100 $\mu\mu$f. Below 100 $\mu\mu$f decreasing sensitivity of balance increases the error inversely with capacitance.



1.31 The detector can be disconnected from the bridge by turning the multiplier switch to the DET position. It can then be used as a null detector for any other 60-cycle bridge. Its input is between DET binding post and G.

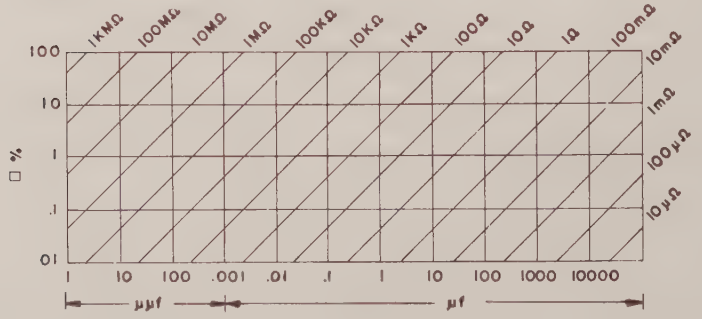


Figure 6. Charts for Determining Graphically R_X in Formula (3.6).

3.34 Dissipation Factors Above 60%: Values of dissipation factor beyond the direct-reading range (60%) of the bridge will occasionally be encountered, particularly for electrolytic capacitors of very high value. The most convenient way of extending the range is by the use of an external parallel resistor, as described in Section 5.7. The dissipation factor of the unknown capacitor is given by:

$$D_X = \frac{1}{R_{NP}\omega C_N} \quad (\Omega, c, f) \qquad (3.7)$$

at 60 cycles

$$D_X = \frac{265.3}{R_{NP}C_N} \quad \% \ (k\Omega, \mu f) \qquad (3.8)$$

where R_{NP} is the added parallel resistance and C_N is the value of the standard capacitor as given in Table I. To measure a dissipation factor of 60% requires 442 kΩ on the four lower multipliers and 4.42 kΩ on the four upper multipliers. The capacitance measured by this method is the parallel capacitance. The relation between series and parallel capacitance is given in Section 4.41, and in Figure 7a (next page).

3.4 MEASUREMENT OF ELECTROLYTIC CAPACITOR WITH POLARIZING VOLTAGE

An external polarizing voltage up to a maximum of 500 volts can be applied to the capacitor under test on the four upper multipliers (1 μf to 11,000 μf).

3.41 D-C Voltage Connection: Connect the external polarizing voltage to the D-C terminals making sure that the proper polarity is observed. The impedance of the power supply or battery used is placed in series with the a-c voltage supply of the bridge and reduces both applied voltage and sensitivity. Sensitivity can be restored by connecting an adequate by-pass capacitor across the D-C terminals.

3.42 Measurement: Proceed with the measurement as in 3.2.

3.43 Caution: The short-circuit current drawn by a defective capacitor may, under certain circumstances, damage the resistance arm, R_B, of the bridge. To minimize this danger, the use of a protective resistor equivalent to 25 ohms per volt in series with the d-c power supply is suggested.

3:44 Leakage Current: The measurement of leakage current of electrolytic capacitors is frequently required in conjunction with the capacitance measurement. The addition of a milliammeter in series with the polarizing voltage source permits this leakage current to be measured at the same time the bridge measurement is made.

3.45 Varying Applied A-C Voltage: In special cases or for certain types of capacitors, the a-c test voltage may be specified, usually not to exceed a certain value. The applied voltage can be decreased by means of a rheostat inserted across the d-c terminals or in series with the external d-c power supply, if one is used.

SECTION 4.0

MEASUREMENTS OF THREE-TERMINAL CAPACITANCE

4.1 THREE-TERMINAL NETWORKS

A problem that occasionally arises is to determine one or all of the capacitances of a three-terminal network as shown in Figures 8a and 8b, having one point grounded.

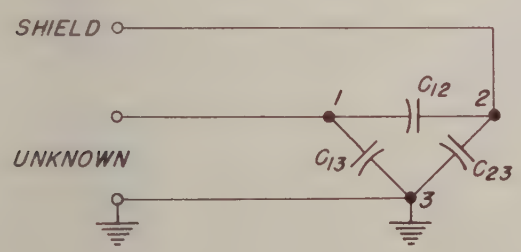


Figure 8a. Equivalent Representation of a Three-Terminal Capacitance, and One Method of Connecting to Bridge.

4.2 USE OF SHIELD TERMINAL

Under certain conditions the capacitance and the dissipation factor of C_{13} (or C_{23}) can be measured directly by connecting the third terminal to the SHIELD terminal of the bridge, as illustrated in Figure 8a.

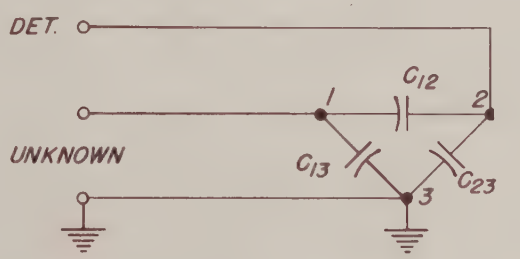


Figure 8b. Alternative Method of Connecting Three-Terminal Capacitance to Bridge.

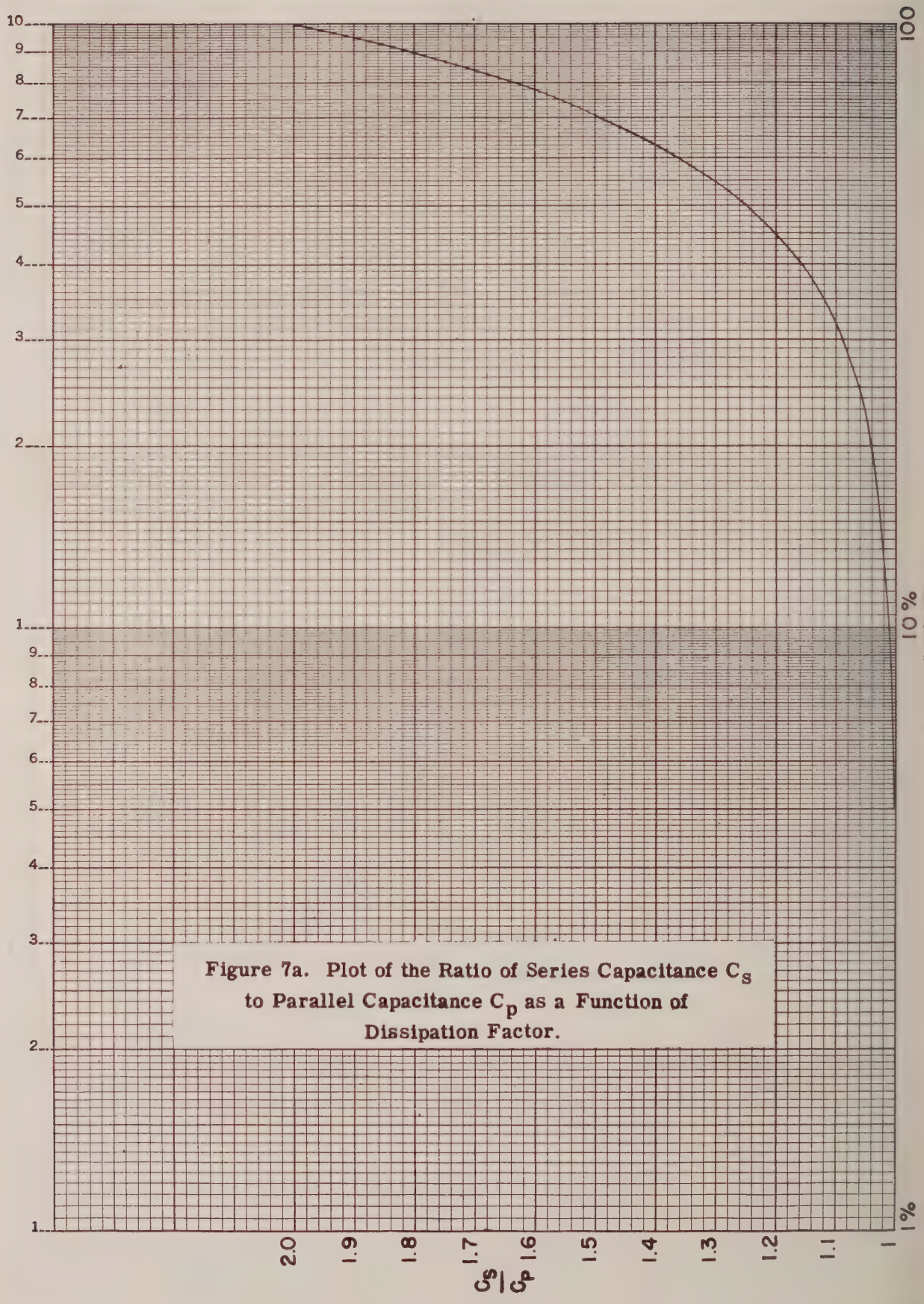


Figure 7a. Plot of the Ratio of Series Capacitance C_s to Parallel Capacitance C_p as a Function of Dissipation Factor.

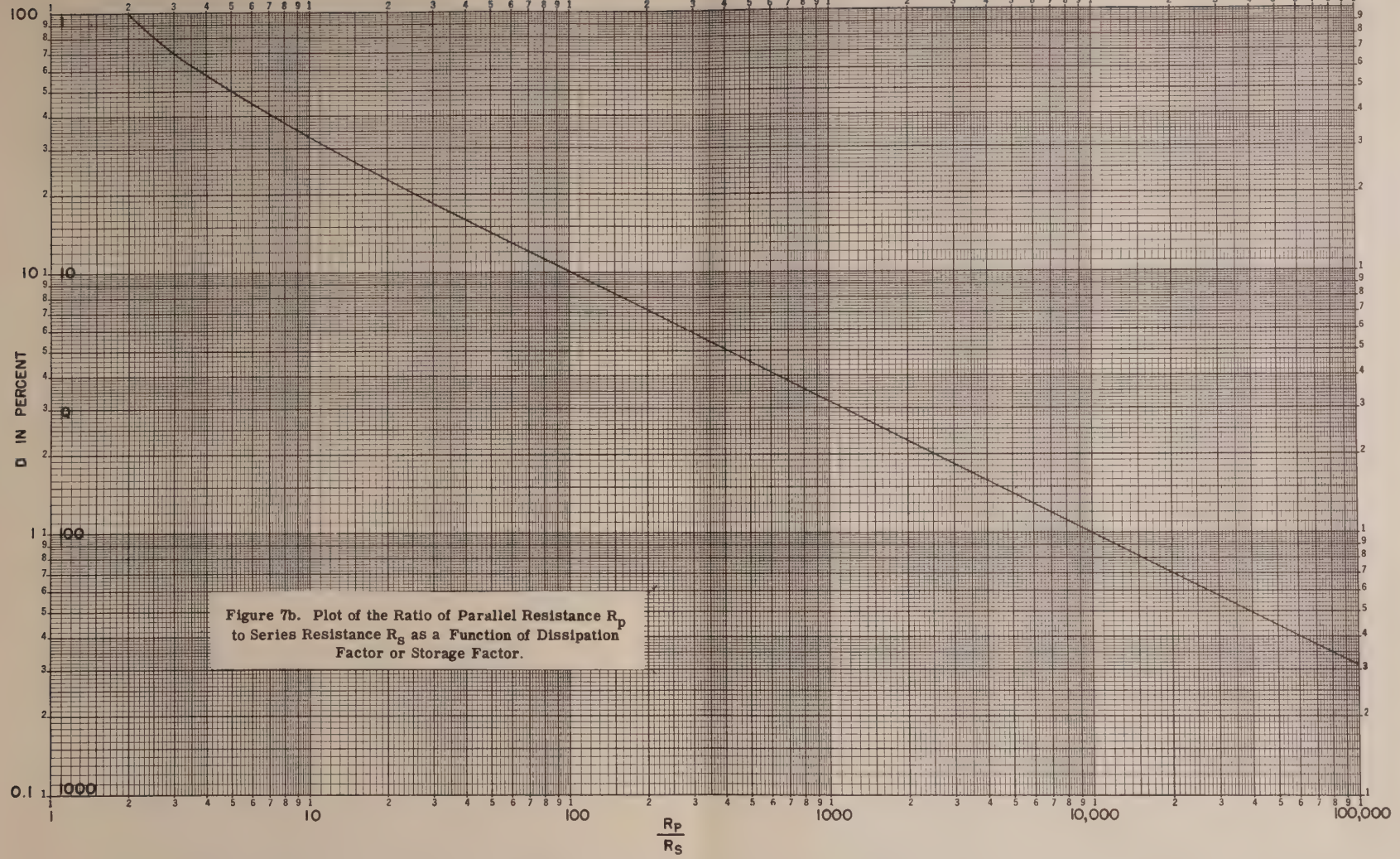


Figure 7b. Plot of the Ratio of Parallel Resistance R_p to Series Resistance R_s as a Function of Dissipation Factor or Storage Factor.

With this connection, the capacitance C_{12} is placed diagonally across the bridge where it has no effect on the measurement. C_{23}, on the other hand, goes directly across the standard arm of the bridge. It will cause both capacitance and dissipation factor to read low by an amount depending on the ratios of C_{23} and D_{23} to the capacitance and dissipation factor of the standard arm. The errors are usually negligible provided C_{23} is less than 100 $\mu\mu$f.

4.3 USE OF DETECTOR TERMINAL

An alternate method of making the above measurement takes advantage of the fact that the fourth corner of the bridge is also available on the panel, at the terminal marked DETector. With the third terminal of the unknown network connected to DETector as in Figure 8b, the capacitance C_{23} is placed diagonally across the bridge and does not affect the measurement. Now, however, the capacitance C_{12} is across the B arm of the bridge. In this position it has little effect on the capacitance balance, buf it causes the dissipation factor to read high by an amount $R_B\omega C_{12}$.

4.4, THE THREE-MEASUREMENT METHOD

To determine accurately all three capacitances of the network of Figures 8a and 8b and their associated dissipation factors, it is necessary to make three measurements as follows:

(A) C_{12} and C_{23} in parallel, by grounding point 1 and measuring from point 2 to ground.

(B) C_{12} and C_{13} in parallel, by grounding point 2 and measuring from point 1 to ground.

(C) C_{13} and C_{23} in parallel, by connecting points 1 and 2 together.

From measurement (A)

$$C_A = C_{12} + C_{23}$$

$$D_A = \frac{D_{12}C_{12} + D_{23}C_{23}}{C_{12} + C_{23}} \qquad (4.1a)$$

From measurement (B)

$$C_B = C_{12} + C_{13}$$

$$D_B = \frac{D_{12}C_{12} + D_{13}C_{13}}{C_{12} + C_{13}} \qquad (4.1b)$$

From measurement (C)

$$C_C = C_{13} + C_{23}$$

$$D_C = \frac{D_{13}C_{13} + D_{23}C_{23}}{C_{13} + C_{23}} \qquad (4.1c)$$

In solving the above set of simultaneous equations, the following expressions are useful:

$$C = 1/2(C_A + C_B + C_C) \qquad (4.2a)$$

$$DC = 1/2(D_AC_A + D_BC_B + D_CC_C) \qquad (4.2b)$$

In terms of these expressions, the three unknown capacitances and dissipation factors can be written as follows, in a form convenient for calculation:

$$C_{13} = C - C_A$$
$$C_{23} = C - C_B$$
$$C_{12} = C - C_C$$
$$D_{13} = \frac{DC - D_AC_A}{C_{13}} \qquad (4.3)$$
$$D_{23} = \frac{DC - D_BC_B}{C_{23}}$$
$$D_{12} = \frac{DC - D_CD_C}{C_{12}}$$

Using these expressions, a convenient tabular form of calculation can be employed, as illustrated by the numerical example given in Table II.

TABLE II

	D	C	DC
C_A	3.0	600	1800
C_B	4.0	500	2000
C_C	3.5	700	2450
Sum		1800	6250
1/2 Sum		900	3125
C_{13}	4.41	300	1325
C_{23}	2.81	400	1125
C_{12}	3.38	200	675

4.41 Effect of Large Dissipation Factors: The formulae of Section 4.0 are developed on the assumption that the measured values are parallel values of capacitance. For values of dissipation factor below 0.10 (10%), the difference between series and parallel components is insignificant. For larger values of dissipation factor, the measured series values of capacitance must be converted to parallel value before using the formulae

of Section 4.4. The conversion formula is

$$C_{xp} = \frac{C_{xs}}{1 + D^2} \qquad (4.4)$$

In equation (4.4), the absolute values of D must be used, equal to the PER CENT reading of the bridge divided by 100. A chart by means of which parallel capacitance can be determined graphically for any pair of values of series capacitance and dissipation factor is given in Figure 7.

SECTION 5.0

OTHER MEASUREMENTS

5.1 THE MEASUREMENT OF INDUCTANCE

5.11 Series-Substitution Method: Inductance can be determined by measuring the net effective capacitance of the unknown inductor in series with a known capacitor of suitable value. The series capacitor must be small enough so that the net reactance of the combination is capacitive. At the same time, it must be large enough so that a significant change in effective capacitance results.

5.111 Connections: The connections shown in Figure 9a are recommended.

5.112 Measurement: Short circuit the inductor and measure the capacitor alone. Denote the bridge readings by C_1,D_1. Remove the short circuit and rebalance the bridge. Denote these readings by C_2, D_2.

5.113 Computation: The series inductance of the inductor is given by

$$L_{xs} = \frac{1}{\omega^2}\frac{\Delta C}{C_1C_2} \quad h\ (c,f) \qquad (5.1)$$

at 60 cycles

$$L_{xs} = 7.04\frac{\Delta C}{C_1C_2} \quad h\ (\mu f) \qquad (5.1a)$$

where $\Delta C = C_2 - C_1$.

The series resistance is given by

$$R_{xs} = \frac{1}{\omega}\frac{D_2C_1 - D_1C_2}{C_1C_2} \quad \Omega\ (c,f) \qquad (5.2)$$

at 60 cycles

$$R_{xs} = 26.53\frac{D_2C_1 - D_1C_2}{C_1C_2} \quad \Omega\ (\%.\mu f) \qquad (5.2a)$$

The storage-factor Q is given by

$$Q_x = \frac{100\Delta C}{D_2C_1 - D_1C_2} \quad (D \text{ in } \%) \qquad (5.3)$$

5.12 Parallel-Substitution Method: Inductance can also be measured by a parallel-substitution method but the conditions regarding the size of the parallel capacitor are the reverse of those stated in 5.11. However, the bridge measures series components and hence, the formulae are rather complicated for the parallel-substitution measurement. The easiest way of handling the computation is probably to convert bridge readings to parallel capacitance by equation (4.4) in Section 4.41.

$$C_{xp} = \frac{C_{xs}}{1 + D^2} \qquad (5.4)$$

5.121 Connections: The connections shown in Figure 9b are recommended.

5.122 Measurement: Make the initial measurement with the high lead of the inductor disconnected. Denote readings by C_1, D_1. Connect the inductor and obtain values D_2, C_2.

5.123 Computation: Convert C_1 and C_2 to effective parallel values by equation (5.4) and call these values C_1' and C_2'.

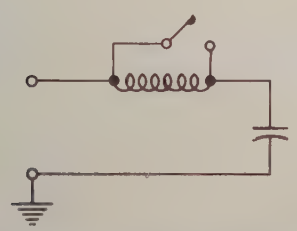


Figure 9a. Connections for Series-Substitution Measurement of Inductance.

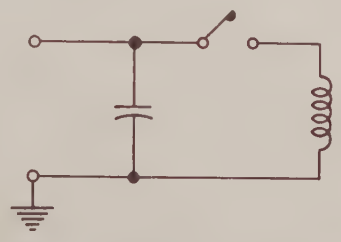


Figure 9b. Connections for Parallel-Substitution Measurement of Inductance.

The parallel inductance is given by

$$L_{xp} = \frac{1}{\omega^2 \Delta C'} \quad h \ (c,f) \qquad (5.5)$$

at 60 cycles

$$L_{xp} = \frac{7.04}{\Delta C'} \quad h \ (\mu f) \qquad (5.5a)$$

where $\Delta C' = C_1' - C_2'$.

The parallel resistance is given by

$$R_{xp} = \frac{1}{\omega} \frac{1}{D_2 C_2' - D_1 C_1'} \ \Omega \ (c,f) \qquad (5.6)$$

at 60 cycles

$$R_{xp} = \frac{265300}{D_2 C_2' - D_1 C_1'} \ \Omega \ (\%, \mu f) \qquad (5.6a)$$

The storage-factor Q is given by

$$Q_x = \frac{1}{D_x} = \frac{100 \Delta C'}{D_2 C_2' - D_1 C_1'} \quad (D \text{ in } \%) \qquad (5.7)$$

The series inductance and series resistance of the inductor can be found from the formulae:

$$L_{xs} = \frac{L_{xp}}{1 + D^2} \qquad (5.8)$$

$$R_{xs} = \frac{R_{xp}}{1 + Q^2} \qquad (5.9)$$

These series values can be determined graphically from the chart of Figure 7.

5.2 THE MEASUREMENT OF RESISTANCE

5.21 Series-Substitution Method: Effective a-c resistance can be measured by the increase in dissipation factor of a capacitor of suitable size when the resistor is connected in series.

5.211 Connections: See 5.111, replacing the inductor by a resistor.

5.212 Measurement: See 5.112, replacing the inductor by a resistor. The two capacitance readings will be identical unless the resistor has a reactive component.

5.213 Computation: The unknown resistance is given by

$$R_{xs} = \frac{\Delta D}{\omega C} \quad \Omega \ (c,f) \qquad (5.10)$$

at 60 cycles

$$R_{xs} = 26.53 \frac{\Delta D}{C} \ \Omega \ (\%, \mu f) \qquad (5.10a)$$

where $\Delta D = D_2 - D_1$ and $C = C_1 = C_2$.

5.22 Parallel-Substitution Method: The unknown resistor may be connected in parallel with the known capacitor.

5.221 Connections: See 5.121, replacing the inductor by a resistor.

5.222 Measurement: See 5.122, replacing the inductor by a resistor.

5.223 Computation: Convert C_1 and C_2 to effective parallel values by equation (5.4). These values will be identical unless the resistor has a large reactive component.

The unknown resistance is given by

$$R_{xp} = \frac{1}{\omega C' \Delta D} \quad \Omega \ (c,f) \qquad (5.11)$$

at 60 cycles

$$R_{xp} = \frac{265300}{C' \Delta D} \quad \Omega \ (\%, \mu f) \qquad (5.11a)$$

where $\Delta D = D_2 - D_1$ and $C' = C_1' = C_2'$.

5.3 THE MEASUREMENT OF DIELECTRIC SAMPLES

The dielectric constant and dissipation factor of an insulating material can be determined from the measurement of the capacitance and the dissipation factor of an elementary capacitor using the material as the insulating medium between metallic electrodes of suitable dimensions.

5.31 Two-Electrode Method: A simple two-electrode system is sufficient for most purposes.

5.311 Preparation of Sample and Affixing of Electrodes:

The calculation of dielectric constant is simplified if the dielectric sample is of such shape that thickness and area are easily measured and calculated; such as a disc or rectangle. If measurements are to be made at other frequencies it is best to use sizes and shapes as recommended in ASTM D-150*. In any case, a more accurate determination of the dielectric constant will be obtained if the dimensions are such that the capacitance is 100 $\mu\mu f$ or greater.

Measure and record the dimensions of the specimen. Clean thoroughly; a mixture of half grain alcohol and half ether is good for this purpose. After the sample is dry apply a very thin film of refined petrolatum to one surface. Place a thin metal foil electrode, preferably less than 1 mil thick, and larger in area than the sample, on this surface. Press the electrode in place with a pad of cloth or squeegee roller and rub out any bubbles so that the foil is in intimate contact with the surface.

*Available from American Society for Testing Materials, 260 Race Street, Philadelphia, Pennsylvania

Trim the foil to the same area as the sample. Apply the other electrode in the same manner.

Electrodes can also be formed by applying with a brush a good silver paint, such as Dupont #4132 Silver Paste, and drying it overnight at 60°C. Such an electrode is porous to moisture, so that the dielectric can be conditioned at any desired relative humidity without removing the electrode.

5.312 Measurement: Proceed as described in Section 3.0 for the measurement of a capacitor.

5.313 Computation: To a first approximation, the dielectric constant K is given by

$$K = \frac{4.45tC}{A} \qquad (\mu\mu f, \text{ in.}) \qquad (5.12)$$

In equation (5.12), A is the area of the electrodes and t the thickness of the material.

5.314 Fringing Effects: A complete discussion of the effects of stray electric field at the edges of the electrodes, and the effect of the capacitance of the high electrode to ground, is given in ASTM D-150.

5.32 Three-Electrode Method (Guard-Electrode Method): The effects of fringing can be substantially eliminated by the use of a three-electrode system. The third electrode is commonly referred to as the guard electrode.

5.321 Circuit Theory and Equivalent Circuit: The guard arrangement is shown schematically in Figure 10. The arrangement is electrically equivalent to the three-terminal capacitance previously discussed in Section 4.1 and shown in Figures 8a and 8b.

In a non-homogenous dielectric the characteristics of the different parts of the sample can be measured by placing the measuring electrodes over the portion to be measured and blocking off the remainder by the guard electrode.

5.322 Measurement: The guard electrode may be connected to the SHIELD terminal, as described in Section 4.2. With this arrangement, the guard-to-ground capacitance is placed across the capacitance arm of the bridge where it will generally have a negligible effect on the measurement.

5.4 MEASUREMENT OF LIQUID INSULATION

Liquid insulation, such as transformer oils and askarels, requires some type of cell for the measurement of its capacitance, dielectric constant, and dissipation factor. The cell in its simplest form can be a multiple plate air capacitor immersed in the liquid, or a grounded cyclindrical can with a slightly smaller insulated cylindrical electrode. Such cells do not allow the accurate calculation of dielectric constant, nor maintain a constant voltage gradient on the liquid. These difficulties are overcome by using a three-electrode cell. Three types of such cells are described in ASTM D-150. They are electrically equivalent to Figure 10 and their terminal capacitances are usually small enough so that the SHIELD electrode can be used as described in Section 4.2.

5.5 MEASUREMENT OF INSULATORS

The measurement of electrical insulators such as bushings and pin-type insulators is carried out as described in Section 3.2, since such insulation has one terminal grounded. The effect of leakage over the surface of the insulation can be removed by placing an electrode around the surface of the insulator and connecting it to the SHIELD terminal, as described in Section 4.2.

5.6 TESTS ON TRANSFORMERS

The insulation in a transformer forms, with the primary and secondary windings and the transformer case, a three-terminal network, such as was defined in Section 4.0. All of the direct capacitances are generally so large that the three measurement methods described in Section 4.4 must be used to separate the three insulations, primary to case, secondary to case, and primary to secondary.

5.61 A sample of the oil in a transformer can be drawn off and tested by the method described in Section 5.4.

5.7 MEASUREMENT OF PARALLEL CAPACITANCE

Effective parallel capacitance can be measured by the use of an external decade-resistance box or other variable resistor, to balance for dissipation factor. Connect the external resistor from SHIELD to ground and set the DISSIPATION FACTOR control to zero. Balance by means of the CAPACITANCE dial and the external resistance.

Used in this way, the CAPACITANCE dial reads directly the parallel capacitance of the unknown and the parallel resistance of the unknown is given by

$$R_{xp} = R_{NP}\frac{R_B}{R_A} \qquad R_{xp} = R_{NP}\frac{C_N}{C_{xp}} \qquad (5.13)$$

In this formula, R_{NP} is the resistance of the external resistance unit, C_{xp} is the capacitance reading in μf,

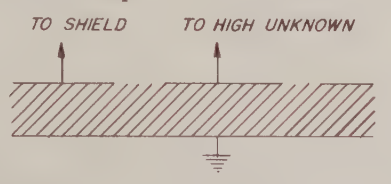


Figure 10. Guard-Electrode Arrangement for Measuring Dielectric Samples.

and C_N the value of standard capacitor as given in Table I.

5.8 USE AS A LIMIT BRIDGE

Because of the limiting characteristics of the null-detector response, the bridge is not as immediately suitable for limit work as one having a linear detector response.

The linear response can readily be obtained by substituting a 6E5 for the 6U5 electron-ray tube, and disconnecting the Thyrite across its grid.

Service and Maintenance Notes

1.0 FOREWORD

1.1 These Service Instructions together with the information given in the Cperating Instructions should enable the user to locate and correct ordinary difficulties resulting from normal usage.

1.2 Most of the components mentioned in these instructions can be located by referring to the photographs, Figures 12, 13, and 14.

1.3 Major service problems should be referred to the Service Department which will cooperate as far as possible by furnishing information and instructions, as well as by shipping any replacement parts which may be required. If the instrument is more than one year old, a reasonable charge may be expected for replacement parts or for complete reconditioning if the bridge is returned.

1.4 Detailed facts giving type and serial numbers of the instrument and parts, as well as operating conditions, should always be included in your report to the Service Department.

2.0 GENERAL

2.1 If the bridge fails to function, check the position of the bridge controls and the condition of the sample under measurement before attempting to locate trouble in the bridge. Failure to obtain a balance may be due to reasons which lie outside the bridge, for instance a short-circuited capacitance sample. Make certain, if possible, that the magnitudes of the impedances of the samples under test do not lie outside the range of the bridge.

2.2 From time to time switch blades, contacts, and contact surfaces of the wire-wound rheostats should be cleaned and lubricated. For cleaning, it is recommended that a solution of half ether and half alcohol be used, followed by a few light strokes with crocus cloth. A very thin smear of petrolatum should then be applied on the wire-wound rheostats.

2.3 A few simple checks should be made before removing the bridge from its carrying case.

2.31 Make certain that the voltage and frequency of the power line source are correct.

2.32 Test the power supply line cord for open circuits or for poor contacts in the power outlets.

2.33 Check the fuses mounted on the top of the panel for open circuits, and be sure they are tight in their clips.

3.0 BRIDGE INOPERATIVE

3.1 Indicating eye does not light; refer to Section 4.0.

3.2 Indicating eye will not deflect properly; bridge lacks sensitivity; refer to Section 5.0.

3.3 Unable to balance bridge on any position of MULTIPLY CAPACITANCE BY switch; refer to Section 6.0.

3.4 Unable to balance bridge on one or more positions of MULTIPLY CAPACITANCE BY switch; refer to Section 7.0.

3.5 Unable to make Zero Adjustment; refer to Section 8.0.

3.6 Calibration of dials; refer to Section 9.0.

3.7 Power supply inoperative; refer to Section 10.0.

3.8 Vacuum-Tube Data; refer to Section 11.0.

4.0 INDICATING EYE DOES NOT LIGHT

4.1 Check tube V-1 and operating voltages; refer to Section 11.0.

4.2 Check that switch S-1 operates properly.

4.3 Test transformer T-1 for open windings and proper connections.

4.4 Test resistor R-1 for open or short circuits and proper value.

4.5 Test capacitor C-1 for open or short circuits and for leakage.

5.0 INDICATING EYE WILL NOT DEFLECT PROPERLY; BRIDGE LACKS SENSITIVITY

5.1 Indicating eye tube V-1 defective; refer to Section 4.0.

5.2 Check tube V-2 and operating voltages; refer to Section 11.0.

5.3 Test rheostat R-3 for open and short circuits and proper operation.

5.4 Test capacitor C-2 for open or short circuits and leakage.

5.5 Test inductor L-1 for open or short circuits.

5.6 Check the contacts and operation of switch S-2, decks number 2 and 3, counting from the panel.

5.7 The gain of the detector circuit can be checked separately by turning switch MULTIPLY CAPACITANCE BY, S-2, to position "D". (For instruments without "D" marking this is the next position clockwise beyond 1000). Apply 0.5 volt, 60 cycles, between the DET terminal and the instrument chassis. The voltage from terminal 3 on V-1 to the chassis should measure approximately 5.0 volts.

5.8 Check resistor R-2. This is a Thyrite resistor whose resistance varies as a non-linear function of the voltage applied across it. With an applied voltage of 1.1 - 3.3 volts the current passed should be about 1 microampere. For 3.8 to 5.2 volts the current should be approximately 10 microamperes.

6.0 UNABLE TO BALANCE BRIDGE ON ANY POSITION OF MULTIPLY CAPACITANCE BY SWITCH

6.1 Be sure that the sample under test is not defective; refer to Section 2.1.

6.2 Test transformer T-2 for continuity of windings and proper connections. Make sure that the inner conductors of the shielded leads to this transformer, and the sheath that connects to SHIELD terminal and S-2, are not grounded.

6.3 Test resistors R-19 through R-31, and R-34 for open or short circuits and proper values.

6.4 Test capacitors C-8 and C-10 through C-15 for open or short circuits and for leakage.

6.5 Check the contacts and operation of switch S-2, decks number 4 and 5, counting from panel.

6.6 Make certain that the UNKNOWN + terminal is not shorted to ground.

6.7 Refer to Sections 4.0 and 5.0.

7.0 UNABLE TO BALANCE BRIDGE ON ONE OR MORE POSITIONS OF MULTIPLY CAPACITANCE BY SWITCH

7.1 Test transformer T-1 for open windings and proper connections.

7.2 Check the contacts and operation of switch S-2, deck number 1.

7.3 Test resistors R-7 through R-10 for open or short circuits and proper values for the particular capacitance range involved.

8.0 UNABLE TO MAKE ZERO ADJUSTMENTS

8.1 Test resistors R-11 through R-18, and R-32 for open and short circuits and proper values.

8.2 Test capacitor C-7 for open or short circuits and leakage.

8.3 Check the contacts and operation of switch S-3.

8.4 Refer to Sections 4.0, 5.0, 6.0, and 7.0.

9.0 CALIBRATION OF DIALS

These calibrations must be made using a Wheatstone bridge accurate to at least $\pm 0.25\%$.

9.1 CAPACITANCE dial

9.11 Make certain that the rheostat, R-19, is clean, that the set screws are tight, and that the cam follower mechanism is operating freely.

9.12 Remove one connection to R-19, and connect the Wheatstone bridge to the rheostat. The resistance, in ohms, measured by the bridge should then be 1000 times the setting of the CAPACITANCE dial.

9.13 Turn the CAPACITANCE dial to a point near the center which brings the cam follower opposite one of the cam plate screws, and adjust the screw until the resistance in ohms is 1000 times the dial reading. Progress up the scale and then down the scale, adjusting each screw in a similar manner. As a final check, see that each main point on the dial and also points 0.5 and 0.1 check within $\pm 0.5\%$ of the correct resistance value. If it is found that the whole cam plate is adjusted too high or too low, loosen the set screws in the dial, shift its position on the shaft, and start the cam plate adjustment over again.

9.2 DISSIPATION FACTOR dial

9.21 Make certain, on each rheostat, that the blade passes from the last wire to the terminal within 1/2 division of where the dial indicates ZERO. If this condition is not met, shift the dial and/or blades until it is. (Note: It is more important that the ZERO of the high-resistance rheostat R-31A, R-31B match the dial.)

9.22 Connect the Wheatstone bridge between ground and the junction of R-26A, R-30, C-13, and C-14. Set the DISSIPATION FACTOR dial to 5% and adjust rheostat R-30 to obtain exactly 132.6 ohms.

Set the dial to 30% and adjust rheostat R-27 to obtain exactly 795.8 ohms.

9.23 Connect the Wheatstone bridge between ground and the junction of R-28, R-31A, and C-12.

Set the DISSIPATION FACTOR dial to 5% and adjust rheostat R-28 to obtain 13,500 ohms.

Set the dial to 30% and adjust rheostat R-29 to obtain 81,100 ohms.

10. POWER SUPPLY INOPERATIVE

10.1 Check tube V-3 and measure operating voltages; refer to Section 11.0.

10.2 Test resistors R-4, R-5, and R-6 for open or short circuits and proper values.

10.3 Test capacitors C-3, C-4, C-5, and C-6 for open or short circuits and leakage.

10.4 Refer to Sections 2.3 and 4.3.

11.0 VACUUM-TUBE DATA

Table of tube socket voltages measured from socket pin to ground, unless otherwise indicated, using a 20,000 ohms-per-volt meter (Weston 772 Analyzer). D-C voltages may vary ±20%.

SYMBOL	TYPE	SOCKET PIN NUMBER								FUNCTION
		1	2	3	4	5	6	7	8	
V-1	6U5	1 and 6 6.3vAC	50v	-6.6	220	0	---	---	---	Indicator
V-2	6SJ7	0	2 and 7 6.3vAC	0	-3.0	0	1.3	---	215	Amplifier
V-3	6X5GT/G	0	2 and 7 6.3vAC	260vAC	---	260vAC	---	---	330	Rectifier

CONDITIONS:

Line voltage	- 115v-60 cycles
DISSIPATION FACTOR Dial	- Maximum
CAPACITANCE Dial	- Maximum
SENSITIVITY Control	- Maximum
MULTIPLY CAPACITANCE BY Switch	- 1

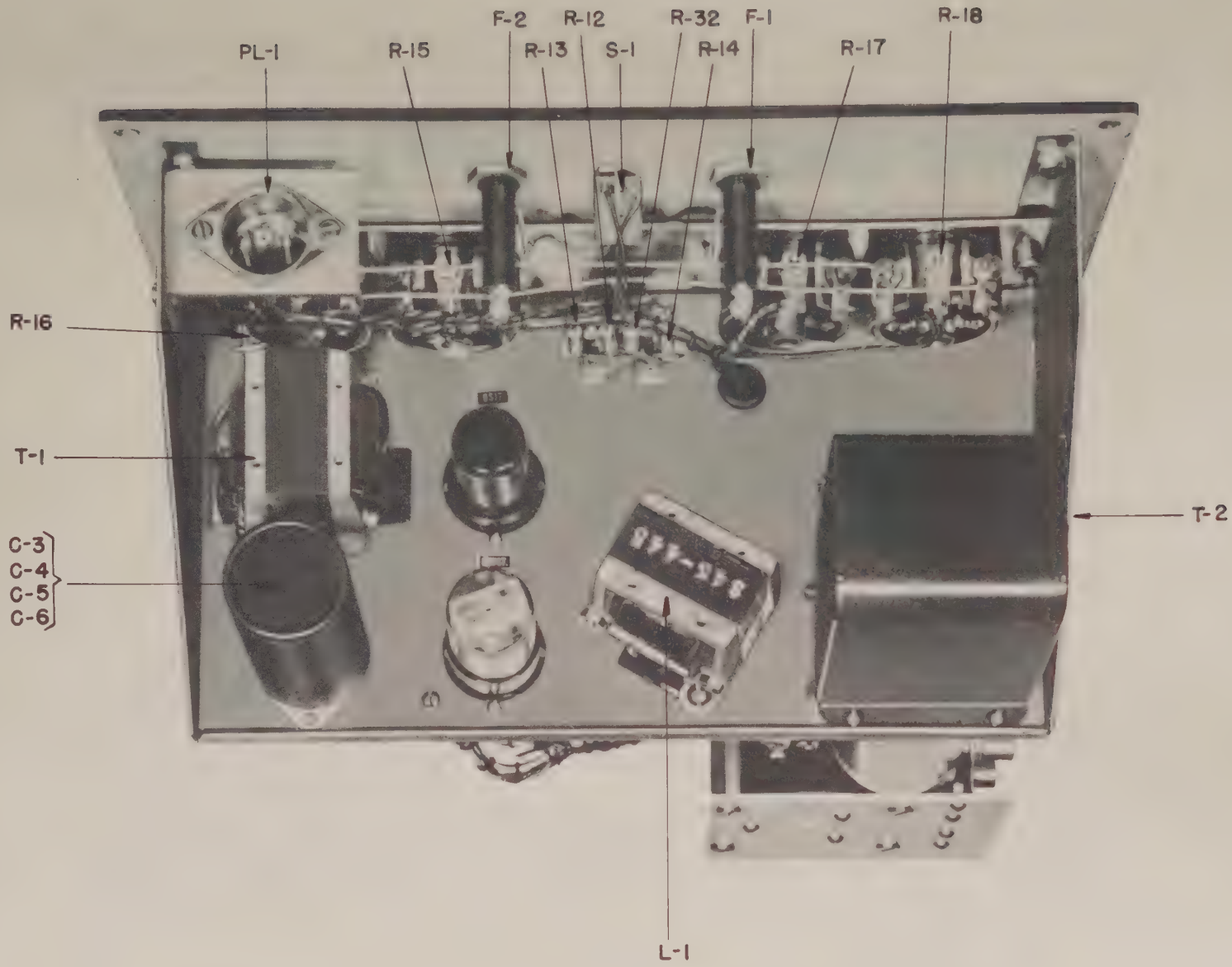


Figure 12. Interior View of Bridge.

PARTS LIST

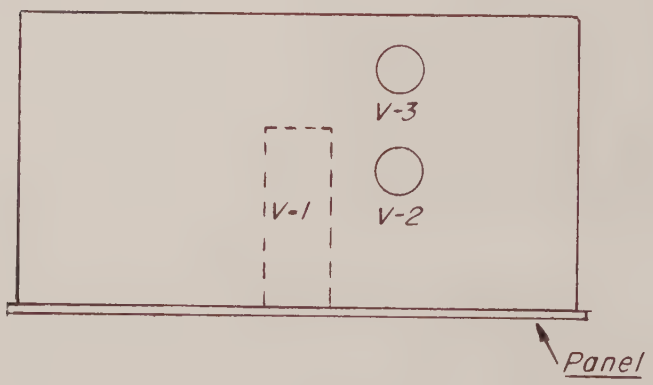
RESISTORS

R-1 = 3.3 MΩ
R-2 = Thyrite
R-3 = 1 MΩ
R-4 = 27 kΩ
R-5 = 27 kΩ
R-6 = 0.56 MΩ
R-7 = 22 kΩ
R-8 = 3.3 kΩ
R-9 = 330 Ω
R-10 = 3.3 Ω
R-11 = 10 MΩ
R-12 = 27 kΩ
R-13 = 27 kΩ
R-14 = 10 kΩ
R-15 = 20 kΩ
R-16 = 20 kΩ
R-17 = 20 kΩ
R-18 = 20 kΩ
R-19 = 11.2 - 11.7 kΩ
R-20 = 10 kΩ
R-21 = 100 kΩ
R-22 = 900 Ω
R-23 = 90 Ω
R-24 = 9 Ω
R-25 = 0.988 Ω
R-26A = 136.6 - 144.6 Ω
R-26B = 710 - 750 Ω
R-27 = 30 kΩ
R-28 = 0.5 MΩ
R-29 = 3 MΩ
R-30 = 5 kΩ
R-31A = 13,980 - 14,760 Ω
R-31B = 73,000 - 77,000 Ω
R-32 = 10 kΩ
R-33 = 3.3 MΩ
R-34 = 1 MΩ
R-35 = 796 Ω
R-36 = 81,100 Ω

CAPACITORS

C-1 = 0.02 μf
C-2 = 0.035 μf
C-3 = 20 μf
C-4 = 20 μf
C-5 = 20 μf
C-6 = 20 μf
C-7 = 0.001 μf
C-8 = 50 μμf
C-10 = .005 μf
C-11 = .0005 μf
C-12 = 0.0099 μf
C-13 = 0.5 μf
C-14 = 0.5 μf
C-15 = 0.01 μf

TUBE LAYOUT



TOP VIEW OF INSTRUMENT

FUSES

For 115-volt input
F-1 = 0.2 amp.
F-2 = 0.2 amp.

For 230-volt input
F-1 = 0.1 amp.
F-2 = 0.1 amp.

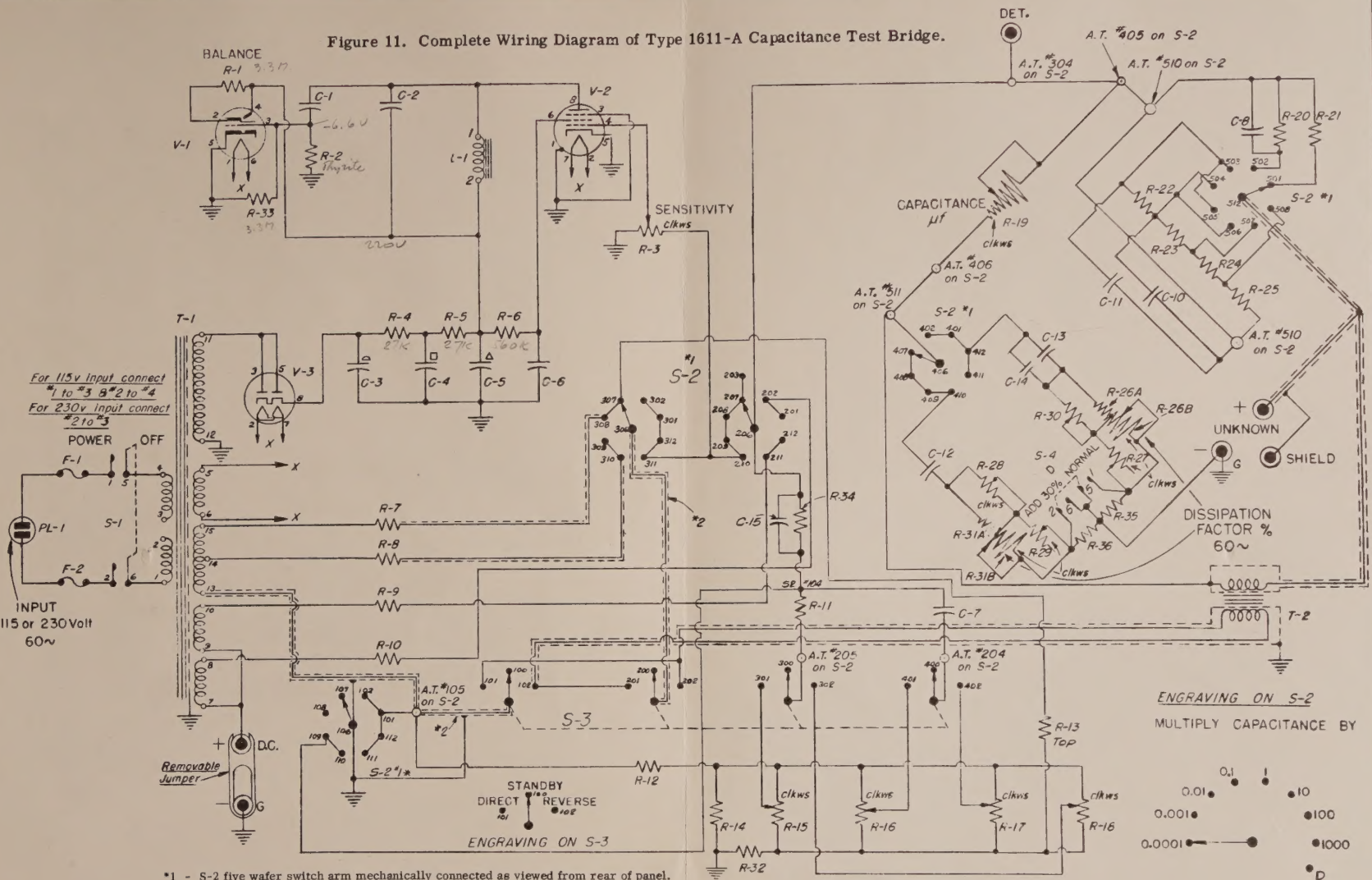
SWITCHES

S-1 = DPST SWT-333
S-2 = SWRW-24
S-3 = SWRW-25
S-4 = DPST SWT-333

TUBES

V-1 = RCA 6U5
V-2 = RCA 6SJ7
V-3 = RCA 6X5-GT/G

Figure 11. Complete Wiring Diagram of Type 1611-A Capacitance Test Bridge.



*1 - S-2 five wafer switch arm mechanically connected as viewed from rear of panel.

*2 - Twin Twisted Conductor Shielded lead from S-2 to S-3.

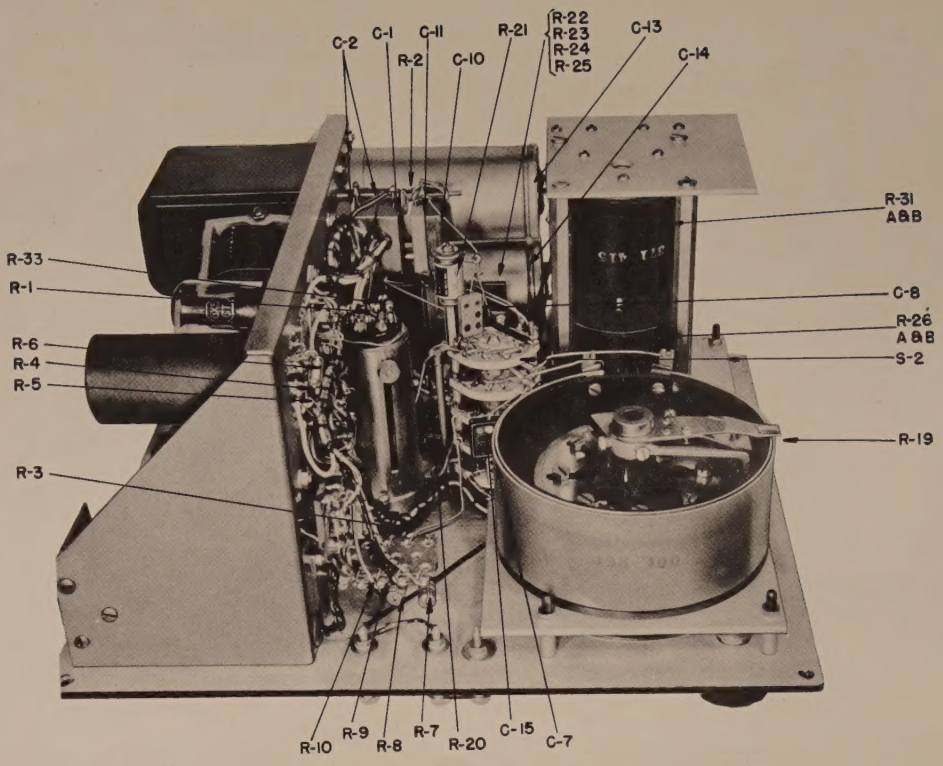


Figure 14. Interior View of Right Side of Bridge.

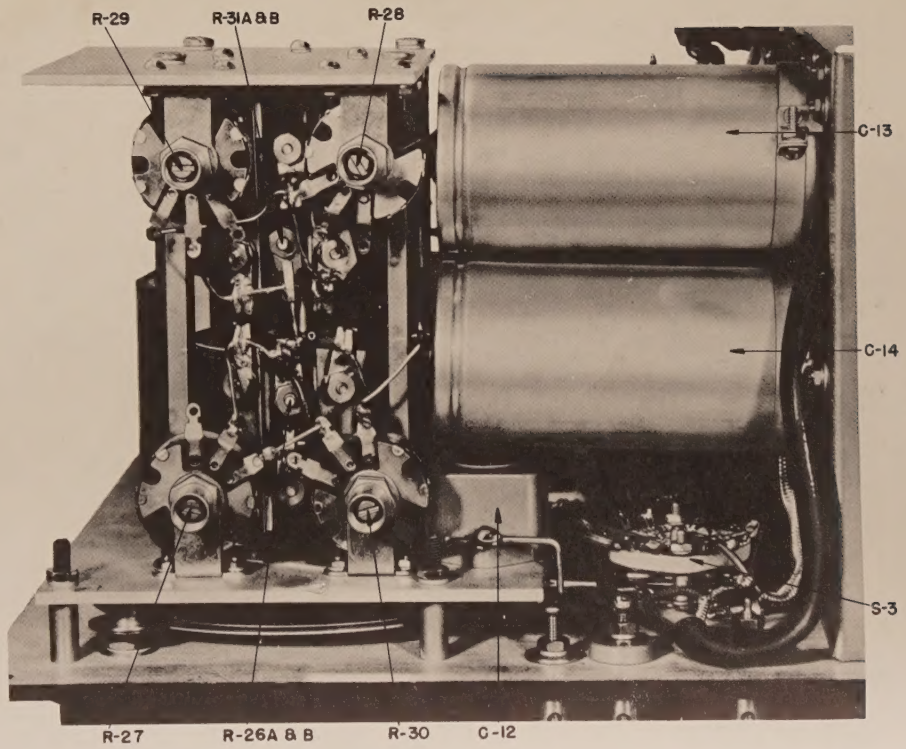


Figure 13. Interior View of Left Side of Bridge.

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